

Modelling and Control of Unmanned Ground Vehicles

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CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and in the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Thanh Hung Tran

Abstract

The thesis focuses on issues of vehicle modelling incorporating wheel-terrain interaction and low-level control design taking into account uncertainties and input time delay. Addressing these issues is of significant importance in achieving persistent autonomy for outdoor UGVs, especially when navigating on unprepared terrains.

The test-bed vehicle used for this research is retrofitted from an all-terrain 20-hp, 0.5-tonne vehicle. Its driveline system consists of an internal combustion engine, continuous variable transmission (CVT), gearbox, differential, chains, and eight wheels. The vehicle is driven in the skid-steering mode, which is popular for many off-road land-vehicle platforms.

In this thesis, a comprehensive approach is proposed for modelling the driveline. The approach considers the difference in speed between two outputs of the differential and the turning mechanism of the vehicle. It describes dynamics of all components in the vehicle driveline in an integrated manner with the vehicle motion. Given a pattern of the throttle position, left and right braking efforts as the inputs, the dynamic behaviour of the wheels and other components of the UGV can be predicted.

For controlling the vehicle at the low level, PID controllers are firstly used for all actuators. As many components of the vehicle exhibit nonlinearities and time delay, the large overshoots encountered in the outputs can lead to undesirable vehicle behaviours. To alleviate the problem, a novel control approach is proposed for suppression of overshoots resulting from PID control. Sliding mode control (SMC) is employed, for this, with time delay compensated by using an output predictor. As a result, the proposed approach can improve significantly system robustness and reduce substantially step response overshoot. Notably, the design is generic in that it can be applied for many dynamic processes.

Knowledge of the interaction between the UGV and the terrain plays an important role in increasing its autonomy and securing the safety for off-road locomotion. In this regard, vehicle kinematic equations are combined with the theory of terramechanics for dynamic modelling of the interaction between the vehicle wheels and a variety of terrain types. Also, a fast algorithm is developed to enable online implementation. The novel interaction model takes into account the relationship between normal stresses, shear stresses, and shear displacement of the terrain that is in contact with the wheels in deriving the three-dimensional reaction forces.

Finally, all modelling and control algorithms are integrated into a unique simulator for emulating the vehicle mobility characteristics. In particular, the wheel's slip and rolling resistance can also be derived to provide useful information for closed-loop control when the UGV is navigating in an unknown environment. The simulator, as a tool for analysing the vehicle mobility, is helpful for further research on relevant topics such as traction control, safe and effective locomotion.

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List of Symbols

Symbols	Nomenclature	Unit
α_i, β_i	Angles of shear stress on the i^{th} wheel in standard spherical coordinates	rad
χ	Ground slope angle	rad
δ	Damping ratio	-
δ_l	Lower limit of damping ratio	-
δ_h	Higher limit of damping ratio	-
$\hat{\delta}$	Approximation of damping ratio	-
ε	Error threshold in search algorithm	%
ϕ	Terrain internal friction angle	rad
γ_i	Angle between slip velocity on the i^{th} wheel and its tangential component	rad
η	SMC parameter	-
φ_i	Elevation angle of shear stress in new spherical coordinates	rad
λ	SMC parameter	-
θ	Angle of wheel contact with terrain	rad
θ_1	Wheel entry angle at first contact point	rad
θ_{1_i}	The i^{th} wheel entry angle	rad
θ_2	Wheel exit angle at last contact point	rad
θ_{2_i}	The i^{th} wheel exit angle	rad
θ_b	Brake actuator position	%
$\theta_{c1_i}, \theta_{c2_i}$	Intersection points between shear stress under the i^{th} wheel and its linearisation	rad
θ_e	Engine throttle position	%
θ_i	The i^{th} wheel contact angle	rad
θ_m	Maximum stress point	rad

Symbols	Nomenclature	Unit
θ_{m_i}	Maximum stress point on the i^{th} wheel	rad
$\theta_{x1_i}, \theta_{x2_i}$	Intersection points between the normal stress distribution under the i^{th} wheel and its linearisation	rad
θ_M	Motor position (throttle control)	%
ρ	Azimuth angle between vehicle frame and earth coordinates	rad
σ	Normal stress under a wheel	kPa
σ_1	Normal stress in front region	kPa
σ_{1_i}	Normal stress in front region under the i^{th} wheel	kPa
$\hat{\sigma}_{1_i}$	Linear approximation of normal stress in front region under the i^{th} wheel	kPa
σ_{1X_i}	Longitudinal component of normal stress in front region under the i^{th} wheel	kPa
σ_{1Z_i}	Vertical component of normal stress in front region under the i^{th} wheel	kPa
$\hat{\sigma}_{1X_i}$	Linear approximation of the longitudinal component of normal stress in front region under the i^{th} wheel	kPa
$\hat{\sigma}_{1Z_i}$	Linear approximation of the vertical component of normal stress in front region under the i^{th} wheel	kPa
σ_2	Normal stress in rear region	kPa
σ_{2_i}	Normal stress in rear region under the i^{th} wheel	kPa
$\hat{\sigma}_{2_i}$	Linear approximation of normal stress in rear region under the i^{th} wheel	kPa
σ_{2X_i}	Longitudinal component of normal stress in rear region under the i^{th} wheel	kPa

Symbols	Nomenclature	Unit
σ_{2Z_i}	Vertical component of normal stress in rear region under the i^{th} wheel	kPa
$\hat{\sigma}_{2X_i}$	Linear approximation of longitudinal component of normal stress in rear region under the i^{th} wheel	kPa
$\hat{\sigma}_{2Z_i}$	Linear approximation of vertical component of normal stress in rear region under the i^{th} wheel	kPa
σ_i	Normal stress under the i^{th} wheel	kPa
σ_{X_i}	Longitudinal component of normal stress under the i^{th} wheel	kPa
σ_{Y_i}	Lateral component of normal stress under the i^{th} wheel	kPa
σ_{Z_i}	Vertical component of normal stress under the i^{th} wheel	kPa
τ	Shear stress	kPa
τ_1	Shear stress in front region	kPa
τ_{1_i}	Shear stress in front region on the i^{th} wheel	kPa
$\hat{\tau}_{1_i}$	Linear approximation of shear stress in front region on the i^{th} wheel	kPa
τ_{1t_i}	Tangential component of shear stress in front region on the i^{th} wheel	kPa
$\hat{\tau}_{1t_i}$	Linear approximation of tangential shear stress in front region on the i^{th} wheel	kPa
τ_{1X_i}	Longitudinal component of shear stress in front region on the i^{th} wheel	kPa
τ_{1Y_i}	Lateral component of shear stress in front region on the i^{th} wheel	kPa
τ_{1Z_i}	Vertical component of shear stress in front region on the i^{th} wheel	kPa

Symbols	Nomenclature	Unit
$\hat{\tau}_{1X_i}$	Linear approximation of longitudinal component of shear stress in front region on the i^{th} wheel	kPa
$\hat{\tau}_{1Y_i}$	Linear approximation of lateral component shear stress in front region on the i^{th} wheel	kPa
$\hat{\tau}_{1Z_i}$	Linear approximation of vertical component shear stress in front region on the i^{th} wheel	kPa
τ_2	Shear stress in rear region	kPa
τ_{2_i}	Shear stress in rear region on the i^{th} wheel	kPa
$\hat{\tau}_{2_i}$	Linear approximation of shear stress in rear region on the i^{th} wheel	kPa
τ_{2t_i}	Tangential component of shear stress in rear region on the i^{th} wheel	kPa
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$\hat{\tau}_{2Y_i}$	Linear approximation of lateral component shear stress in rear region on the i^{th} wheel	kPa
$\hat{\tau}_{2Z_i}$	Linear approximation of vertical component of shear stress in rear region on the i^{th} wheel	kPa

Symbols	Nomenclature	Unit
τ_e	Engine time constant	s
τ_i	Shear stress on the i^{th} wheel	kPa
τ_m	Motor time constant	s
τ_{t_i}	Tangential component of the shear stress on the i^{th} wheel	kPa
τ_{x_i}	Longitudinal component of shear stress on the i^{th} wheel	kPa
τ_{y_i}	Lateral component of shear stress on the i^{th} wheel	kPa
τ_{z_i}	Vertical component of shear stress on the i^{th} wheel	kPa
ω_e	Engine rotational speed	RPM
ω_c	CVT output speed	RPM
ω_d	Rotational speed of differential's case	RPM
ω_{dL}	Differential's output speed on left side	RPM
ω_{dR}	Differential's output speed on right side	RPM
ω_G	Gearbox output speed	RPM
ω_n	Natural frequency	rad/s
ω_{n1}	Lower limit of natural frequency	rad/s
ω_{n2}	Higher limit of natural frequency	rad/s
$\hat{\omega}_n$	Approximation of natural frequency	rad/s
ω_i	Speed of the i^{th} wheel	rad/s
ω_w	Wheel rotational speed	rad/s
ω_{wL}, ω_L	Left wheel rotational speed	rad/s
ω_{wR}, ω_R	Right wheel rotational speed	rad/s
Ω	Vehicle turning rate	rad/s
a	Longitudinal distance between successive wheel axles	m

Symbols	Nomenclature	Unit
a_X	Vehicle acceleration along longitudinal direction	m/s
a_Y	Vehicle acceleration along lateral direction	m/s
b	Wheel width	m
b_e	Engine damping coefficient	Nms
b_d	Differential damping coefficient	Nms
b_w	Wheel damping coefficient	Nms
$b_{D,in}$	Damping coefficient inside differential	Nms
b_G	Gearbox damping coefficient	Nms
c	Terrain cohesion parameter	kPa
c_{r1}, c_{r2}	Wheel friction coefficients	$m.s^{-2}, s^{-1}$
d	Distance between the vehicle centroid and the centre of mass	m
dA_i	Area increment around a contact point	m^2
dF_{X_i}	Total force increment along longitudinal direction acting on a very small contact area around a contact point	N
dF_{Y_i}	Total force increment along lateral direction acting on a very small contact area around a contact point	N
dF_{Z_i}	Total force increment along vertical direction acting on a very small contact area around a contact point	N
e	Control error	
e_{emf}	Motor back electromotive force	V
e_o	PID error	
f	Nonlinear function	-
\hat{f}	Approximation of nonlinear function	-
g	Gravitational acceleration	m/s^2

Symbols	Nomenclature	Unit
h	Height of the centre of mass above the ground	m
i	Vehicle wheel slip	%
i_{CVT}	CVT belt slip	%
j	Shear displacement	m
j_i	Shear displacement at a contact point on the i^{th} wheel	m
j_{X_i}	Shear displacement at a contact point on the i^{th} wheel along longitudinal direction	m
j_{Y_i}	Shear displacement at a contact point on the i^{th} wheel along lateral direction	m
j_{Z_i}	Shear displacement at a contact point on the i^{th} wheel along vertical direction	m
k	SMC parameter / time step	-
$k_{1_i}, k_{2_i}, c_{1_i}, c_{2_i}$	Linearisation parameters for normal stress on the i^{th} wheel	kPa/rad, kPa/rad, kPa, kPa
$k_{1X_i}, k_{2X_i}, c_{1X_i}, c_{2X_i}$	Linearisation parameters for longitudinal component of normal stress on the i^{th} wheel	kPa/rad, kPa/rad, kPa, kPa
$k_{1Z_i}, k_{2Z_i}, c_{1Z_i}, c_{2Z_i}$	Linearisation parameters for lateral component of normal stress on the i^{th} wheel	kPa/rad, kPa/rad, kPa, kPa
$k_{3_i}, k_{4_i}, c_{3_i}, c_{4_i}$	Linearisation parameters for shear stress on the i^{th} wheel	kPa/rad, kPa/rad, kPa, kPa
$k_{3t_i}, k_{4t_i}, c_{3t_i}, c_{4t_i}$	Linearisation parameters for tangential component of shear stress on the i^{th} wheel	kPa/rad, kPa/rad, kPa, kPa
$k_{3X_i}, k_{4X_i}, c_{3X_i}, c_{4X_i}$	Linearisation parameters for longitudinal component of shear stress on the i^{th} wheel	kPa/rad, kPa/rad, kPa, kPa
$k_{3Y_i}, k_{4Y_i}, c_{3Y_i}, c_{4Y_i}$	Linearisation parameters for lateral component of shear stress on the i^{th} wheel	kPa/rad, kPa/rad, kPa, kPa
$k_{3Z_i}, k_{4Z_i}, c_{3Z_i}, c_{4Z_i}$	Linearisation parameters for vertical component of shear stress on the i^{th} wheel	kPa/rad, kPa/rad, kPa, kPa

Symbols	Nomenclature	Unit
k_c, k_ϕ	Pressure-sinkage moduli parameters of a terrain	$\text{kN/m}^{n+1}, \text{kN/m}^{n+2}$
m	Vehicle's mass	kg
m_w	Wheel's mass	kg
n	Sinkage exponent parameter of terrain	-
r	Wheel radius	m
t_d	Time delay	s
t_P	Peak time	s
u	SMC output, PID input	%
u_{eq}	Equivalent control output	%
u_R	Robust control output	%
x	Speed difference between the differential's case and its outputs	RPM
(x_i, y_i)	Cartesian coordinates of a contact point on the i^{th} wheel frame	m
$\mathbf{x}(t)$	State variable vector	
y	Process output	%
y_d	Desired output (Reference or set-point)	%
z	Wheel sinkage	m
z_i	Sinkage of the i^{th} wheel	m
A, B	System matrices in state space form	
B	Half of the vehicle track	m
B_m	Motor damping ratio	Nms
D	Boundary of disturbance	
F	Boundary of nonlinear function's approximation error	-
F_R	Wheel rolling resistance	N
$F_{t,w}$	Traction force at wheels	N
F_{X_i}	Total reaction force acting on the i^{th} wheel along longitudinal direction	N

Symbols	Nomenclature	Unit
\hat{F}_{X_i}	Estimate of total reaction force acting on the i^{th} wheel along longitudinal direction	N
F_{Y_i}	Total reaction force acting on the i^{th} wheel along lateral direction	N
\hat{F}_{Y_i}	Estimate of total reaction force acting on the i^{th} wheel along lateral direction	N
F_{Z_i}	Total reaction force acting on the i^{th} wheel along vertical direction	N
\hat{F}_{Z_i}	Estimate of total reaction force acting on the i^{th} wheel along vertical direction	N
I	Motor armature current	A
I_Z	Vehicle moment of inertia around Z axis	kg.m ²
J_e	Engine moment of inertia	kg.m ²
J_m	Motor rotor's moment of inertia	kg.m ² s ⁻²
J_w	Wheel moment of inertia	kg.m ²
K	Shear deformation modulus	m
K_1	CVT gear ratio	-
K_2	Gearbox gear ratio	-
K_3	Chain system gear ratio	-
K_a	Amplifier' voltage to current gain	AV ⁻¹
K_e	Engine gain	N.m
$K_{em}=K_t$	Motor electromotive force constant	N.m.A ⁻¹
K_i	Actuator's current to force gain	NA ⁻¹
K_m	Motor gain	-
K_D	Derivative gain (D)	-
K_I	Integral gain (I)	-
K_G	Motor gear ratio	-
K_P	Proportional gain (P)	-
L_m	Motor electric inductance	H
M_P	Percentage of overshoot	%

Symbols	Nomenclature	Unit
M_R	Moment of turning resistance	N.m
M_X	Rolling moment around X axis	N.m
M_Y	Rolling moment around Y axis	N.m
M_Z	Turning moment around Z axis	N.m
\hat{M}_Z	Estimate of turning moment	N.m
(N, E)	Position of the vehicle in earth coordinates	m, m
R_m	Motor electric resistance	Ω
T	Traction torque	N.m
T_{bL}	Left brake torque	N.m
T_{bR}	Right brake torque	N.m
T_c	Load on CVT	N.m
T_d	Load on differential's case	N.m
T_{dL}	Load on differential's left output	N.m
T_{dR}	Load on differential's right output	N.m
T_e	Engine generated torque	N.m
T_{ec}	Load on engine	N.m
$T_{fric,e}$	Engine friction torque	N.m
$T_{fric,D}$	Differential friction torque	N.m
$T_{fric,G}$	Gearbox friction torque	N.m
T_i	Traction torque developed on the i^{th} wheel	N.m
\hat{T}_i	Estimate of traction torque developed on the i^{th} wheel	N.m
T_m	Motor torque	N.m
T_{sL}	Total load torque on the left sun gear (differential)	N.m
T_{sR}	Total load torque on the right sun gear (differential)	N.m
T_w	Total load torque on all wheels	N.m
T_{wL}	Load torque from left wheels	N.m
T_{wR}	Load torque from right wheels	N.m

Symbols	Nomenclature	Unit
T_G	Load torque on gearbox	N.m
V	PID output (Process input, or Voltage)	V
\mathbf{V}	Vehicle velocity vector	m/s
V_{jX_i}	Longitudinal component of slip velocity of a contact point on the i^{th} wheel	m/s
V_{jY_i}	Lateral component of slip velocity of a contact point on the i^{th} wheel	m/s
V_{jZ_i}	Vertical component of slip velocity of a contact point on the i^{th} wheel	m/s
V_{t_i}	Tangential component of slip velocity of a contact point on the i^{th} wheel	m/s
V_L	Lyapunov function	-
V_E	Vehicle velocity along east direction	m/s
V_N	Vehicle velocity along north direction	m/s
V_X	Vehicle longitudinal velocity	m/s
V_Y	Vehicle lateral velocity	m/s
S	Sliding surface	-
S_{X_i}	Wheel slip ratio along longitudinal direction	%
S_{Y_i}	Wheel slip ratio along lateral direction	%
(X_i, Y_i, Z_i)	Cartesian coordinates of a contact point on the vehicle frame	m
W	Vehicle weight	N
W_i	Vertical load on the i^{th} wheel	N

Abbreviations

ALV	Autonomous Land Vehicle
CCD	Charge-Coupled Device
CVT	Continuous Variable Transmission
DARPA	Defense Advanced Research Projects Agency
FLIR	Forward Looking InfraRed
HMMWV	High-Mobility, Multipurpose, Wheeled Vehicle
LADAR	Light Detection And Ranging
MIMO	Multiple-Input Multiple-Output
MVEM	Mean Value Engine Model
SSV	Semiautonomous Surrogate Vehicle
SI	Spark Ignition
SMC	Sliding Mode Controller
PID	Proportional – Integral – Derivative
UGV	Unmanned Ground Vehicle